REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 22-09-2009	**2. REPORT TYPE** Final Report	**3. DATES COVERED** *(From – To)* 15 August 2006 - 15-May-07

4. TITLE AND SUBTITLE

Characterizing Sunspot Complexity for Space Weather Applications

5a. CONTRACT NUMBER FA8655-06-M-4006

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
Unit 4515 BOX 14
APO AE 09421

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
SPC 06-4006

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report results from a contract tasking Imagine Technologies Ltd as follows: Months 1-3. Collect and Process GONG and SOHO/MDI magnetograms: Ten years of solar magnetic field measurements from the Michelson Doppler Imaginer (MDI) onboard the ESA/NASA Solar and Heliospheric Observatory (SOHO) will be collected, together with complimentary magnetograms from the global network of ground-based magnetographs, GONG. Using sunspot positions from daily USAF/NOAA Solar Region Summaries, a magnetogram will be extracted for each region over this ten-year period. This will result in a sample size of close to 10,000 sunspots groups. Sunspot magnetograms will then be corrected for line-of-site effects, by applying a cosine correction to the data. Sunspots at high latitudes or at longitudes of greater that approximately +/-60 degrees will be disregarded from our sample, due to the uncertainty associated with reconstructing their true magnetic fields. Each of these steps will be carried out using existing software from the SolarSoftWare library in addition to some additional purpose-written routines.

15. SUBJECT TERMS
EOARD, Solar Monitoring, Solar Physics

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18, NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT UNCLAS	**b. ABSTRACT** UNCLAS	**c. THIS PAGE** UNCLAS	UL	10	BARRETT A. FLAKE
					19b. TELEPHONE NUMBER *(Include area code)* +44 (0)1895 616144

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

EOARD CONTRACT SPC 064006

Characterising Sunspot Complexity for Space Weather Applications

Final Report

COVERING PERIOD JANUARY 2007 THROUGH JANUARY 2008

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Abstract

Fractal and multifractal methods are used to examine the changing complexity of active regions on the solar disk. It is shown that to accurately recover the fractal and multifractal spectrum of the active regions, it is necessary to remove contribution to the spectrum from the surrounding quiet Sun features. A segmentation method in wavelet modulus space is presented to remove the quiet Sun contributions from the subsequent calculations. The method is shown to greatly increase the accuracy of the spectrum and allows for accurate comparison of an active regions multifractal characteristics and its probability to flare.

1 Introduction

Solar active regions are highly dynamic complex systems that have been studied with varying degrees of success using the fractal and multifractal tools. One of the main disadvantages of current methods is their inability to distinguish and separate quiet Sun features from those of active regions. Quiet Sun magnetic features are shown to be statistically different from that of active regions. As such, methods which fail to separate quiet Sun features from the calculation of the active region fractal and multifractal parameters have decreased accuracy. Using the proposed segmentation and multifractal methods, a correlation is presented between the multifractal parameters and active region flaring.

Natural systems are complex and chaotic in their behaviour. As such, simple mathematical tools are unable to describe them accurately. Fractals were first proposed to solve this issue in the study of turbulence and complexity (Schroeder, 1991; Mandelbrot, 1977). Fractals are self-similar objects, meaning that at each level of detail a similar pattern or structure is observed. Fractals described the geometry of an object at each of these scales and are related to an objects Euclidean geometry. As such, lines and squares have fractal dimensions of one and two respectively. An object with a fractal dimension less than one has less detail than a line and is *dust-like*. Objects with fractal dimensions between one and two have more detail in their structure than that of a line but do not occupy fully the space of a square.

Multifractal are a natural extension to the fractal idea, developed to characterise systems with more than one fractal dimension, as found in chaotic dynamical systems (Mandelbrot, 1974). Multifractal objects have a spectrum of fractal dimensions. Each fractal dimension contributes with varying degrees of importance to the overall design and structure of the system.

2 Methods

Fractals and multifractals measure the detail across scale of self-similar objects. In this section, the traditional box-counting algorithm is described and associated problems discussed. In addition a brief overview of the more advanced wavelet modulus maximum method (WTMM) presented. A segmentation method is present which further increases the accuracy of the WTMM method.

2.1 Box-counting

Traditionally, an objects fractal dimension can be calculated by covering it with boxes of varying size ϵ. The fractal dimension is then given by the scaling relation:

$$N(\epsilon) \propto \epsilon^{-D}, \tag{1}$$

where D is the fractal dimension, and $N(\epsilon)$ is the number of boxes of size ϵ. From this, it is straight forward to show that a line has a fractal dimension of one as the number of boxes required scales linearly, similarly for a square the scaling relation is quadratic and has a fractal dimension of two.

Multifractals, like fractals, relate the number of boxes $N(\epsilon)$ to the size of each box ϵ and are characterised by a similar equation:

$$N(\epsilon) \propto \epsilon^{-f(\alpha)}, \tag{2}$$

where instead of a single exponent, there is a spectrum of exponents $f(\alpha)$, each with a relative strength or significance α.

An overview of the box-counting method as applied to solar line-of-sight magnetogram data is provided in (Conlon et al., 2008). Briefly, the main steps are to calculate the:

1. magnetic field with each box i of size ϵ, $B_\epsilon(i)$.
2. partition function for each box size ϵ, $z_\epsilon(q)$.
3. normalised flux for eacbox i of size ϵ, $\hat{B}_\epsilon(i)$.

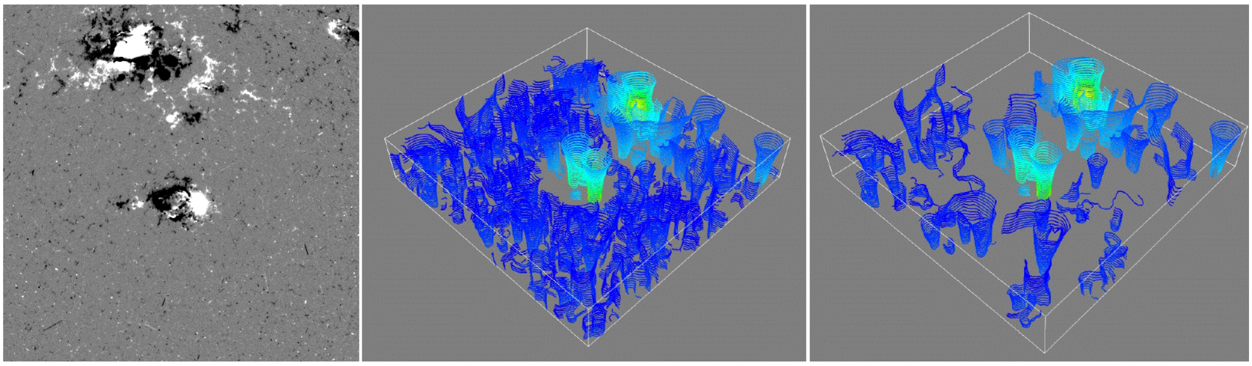

Fig. 1: Left: MDI magnetogram taken 28 October 2003. Center: Wavelet modulus used in the fractal calculations with no segmentation. Right: Wavelet modulus used in the fractal calculations following segmentation Kestener et al. (2009).

4. strength or significance of a measure, $\alpha(q)$.
5. distribution of points of a given concentration strength, $f(\alpha)$.

$f(\alpha)$ for $q = 0$ corresponds to the Hausdroff or fractal dimension.

Due to the discrete nature of the box-counting method, it has many associated errors (Conlon et al., 2008; Alber & Peinke, 1998). Methods have been developed to overcome these discritisation errors and results show they can successfully return the entire or part of the multifractal spectrum. However, these methods tend to be finally tuned for the specific data sets used.

In addition, there is a added error due to possible mixing of fractal and multifractal spectrums, either due to noisy data or the embedding of the system in question within another surrounded system. Previously this error was reduced by limiting the field of view to only cover the object in question. However given the fractal geometry of the object in question these results can vary.

2.2 Wavelet Modulus Maximum Method (WTMMM)

In order to overcome the discrete nature of the box-counting method a wavelet based method was developed. The wavelet modulus maximum method (WTMM) method replaces the boxes from the traditional box-counting method with wavelets. Wavelets have the advantage of been defined for both finite and discrete domains, and in term as a fuzzy boxes. The wavelet based method however returns the so-called singularity spectrum, $D(h)$. This differs from the multifractal spectrum, $f(\alpha)$ as follows:

$$f(\alpha) = D(h), \tag{3}$$

$$\alpha = h + Dimension(image), \tag{4}$$

where h is the Hölder exponent. In order to calculate the $D(h)$ singularity spectrum a 2D WTMM method developed by Arneodo, A., & Decoster, N. (2000) is used. An overview of the WTMM method is provided in Kestener et al. (2009). Briefly the main steps of the WTMM method are:

1. Compute of the 2D continuous wavelet transform of the input image.
2. Extract the WTMM edges at each scale.
3. Calculate the local maximum along the wavelet transform (WT) skeleton and their linking across each scale.
4. Calculate the partition functions from the WT skeleton.
5. Calculate the remaining fractal and multifractal parameters.

As mentioned already, another major source of error in the calculation of fractal and multifractal properties is the contribution from alien process altering the true spectrum. In order to overcome this, a segmentation in wavelet modulus space is proposed. This methods requires that the two process, in this case active and quite Sun magnetic features, are significantly separate and distinct from each other in some wavelet modulus space. Kestener et al. (2009) found this for a quite and active region magnetic field and proposed at cut off at a modulus strength of 40. The segmentation method is shown to greatly increase the accuracy of the returned multifractal spectrum for both test and real data. An example of the segmentation methods ability to selectively extract wavelet modulus related to active region is shown in Figure 1. As is shown the segmentation method selects wavelet modulus related to the active regions feature on the solar disk and removes weaker modulus related to the quiet Sun.

3 Results

This work represent an overview of a much larger body of work (Conlon et al., 2009; Kestener et al., 2009), which has shown the WTMM and the associated segmentation method to be a stable and accurate mathematical tool for the analysis of magnetic fields on the solar disk. Two examples are now described in detail. These example further highlight the proposed thresholds of, $D(h) > 1.2$ and $h > -0.7$ as indicator of increased flaring potential.

3.1 NOAA 10488

NOAA 10488 emerged onto the solar disk on the 26 October 2003 and continued to grow rapidly until the 29 October 2003 (Figure 2). The ability of the segmentation methods to detect the presense of active regions in quiet Sun data is highlight by the rise in $D(h)$ and h prior to the increase in the other physical parameters. Prior to the regions emergence only a limited number of wavelet modulus moments exceed the threshold, resulting in $D(h)$ and h values that would characterise poorly resolved *dusty* data. As the regions forms and develops into a coherent structure the fractal dimension and Hölder exponent rise steadily.

While on disk NOAA 10488 underwent two flaring periods. The first occurred over an eighteen hour period starting at 14:02 UT on the 27 October 2003 and contained five C-class flares and a M1.9 flare. The second started at 18.10 UT on the 29 October 2003, lasted for two days and resulted in 8 C-class flares and two M-class flares. During the regions evolution the associated fractal dimension, $D(h)$, is seen to increase above the proposed threshold for flaring (McAteer, Gallagher, and Ireland, 2005). In addition flaring periods are also associated a Hölder exponent, h, greater than the proposed threshold of Conlon et al. (2009). Given that the Hölder exponent relates the continuity of the underlying magnetic field, a Hölder exponent close to 0 represents magnetic features characteristic of large gradient or step-like-functions.

3.2 NOAA 10953

NOAA 10953 rotated onto the solar disk on the 25 April 2007 already fully developed. While on disk NOAA 10953 underwent no flaring periods during the reported observation. Figure 3 highlights the changing fractal dimension and Hölder exponent of NOAA 10953. At no time during the observation period was both the regions fractal dimension and Hölder exponent greater than the proposed threshold from Conlon et al. (2009). Compared with the results from Conlon et al. (2009) this is further evidence that the proposed threshold are a valid indicator for a regions ability to flare.

4 Future Direction

The results represented here and in Conlon et al. (2009); Kestener et al. (2009) are related to a single point on the multifractal spectrum, $q = 0$. The study of the remaining parts of the multifractal spectrum is left for a later date.

These results further highlight the ability of multiscale methods to detect characteristics changes in the make-up of elements with active region on the photosphere. Together with other physical parameters, the multifractal spectrum may make it possible to detect conditions favourable to flaring in an active region. Further work is required to validate and constrain any thresholds that may or may not exist in reality.

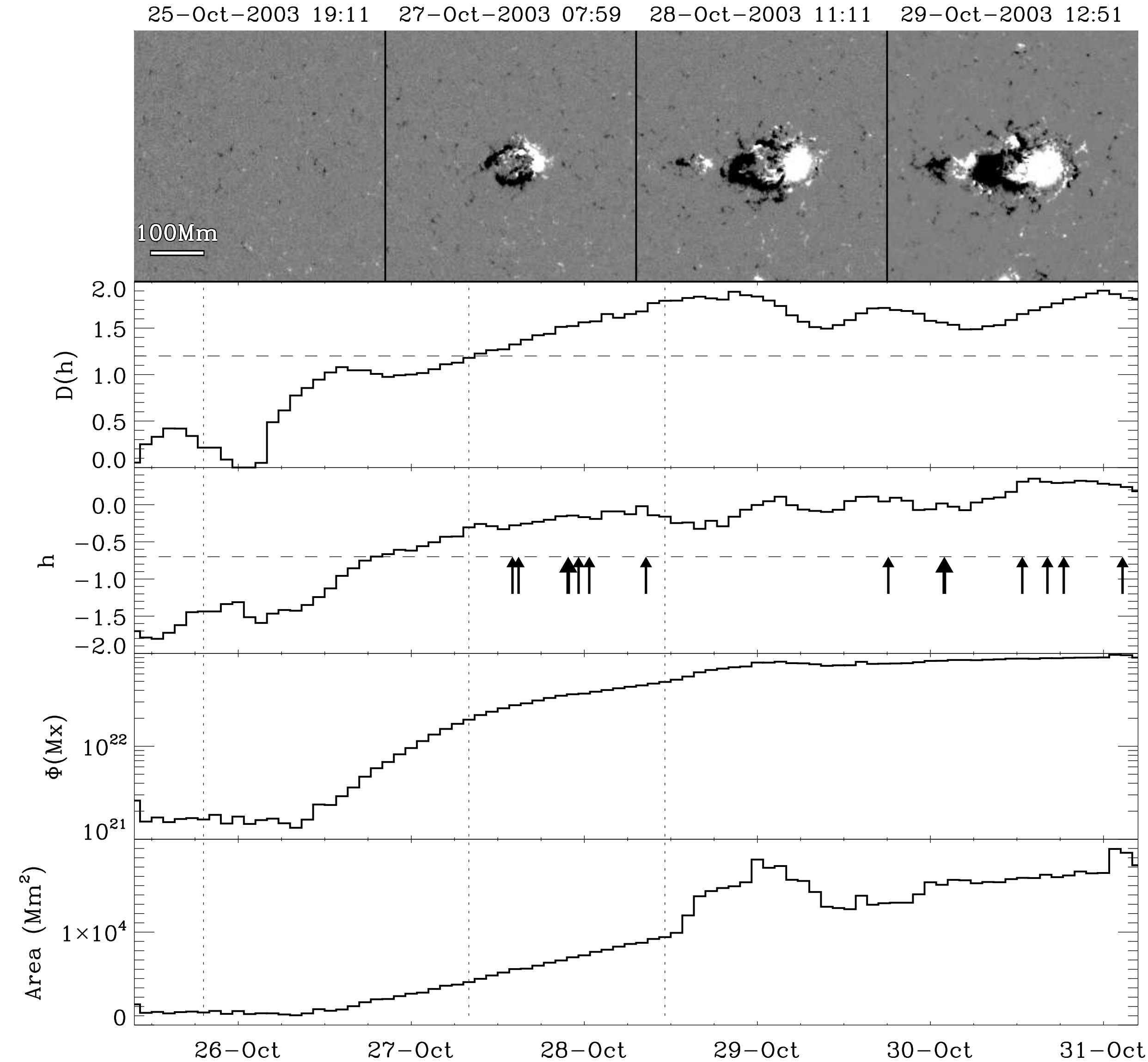

Fig. 2: The evolution of NOAA 10488. (Top panel) MDI magnetogram image for NOAA 10488 on 25 October 2003 at 19:11 UT, 27 October 2003 at 07:59 UT, 28 October 2003 at 11:11 UT and 29 October 2003 at 12:51 UT. (Second panel) $D(h)$ for $q = 0$. (Third panel) h for $q = 0$. (Fourth panel) The total unsigned magnetic flux (Mx). (Bottom panel) Total area (Mm^2). Associated C-class flares are indicated by thin arrows; bolder arrows indicate M-class flares. Vertical dotted lines indicate the time of MDI magnetograms in the regions evolution. Dashed horizontal line in the first panel highlight a previously proposed threshold for flaring (McAteer, Gallagher, and Ireland, 2005). Dashed horizontal line in the second panel shows our proposed threshold. Conlon et al. (2009)

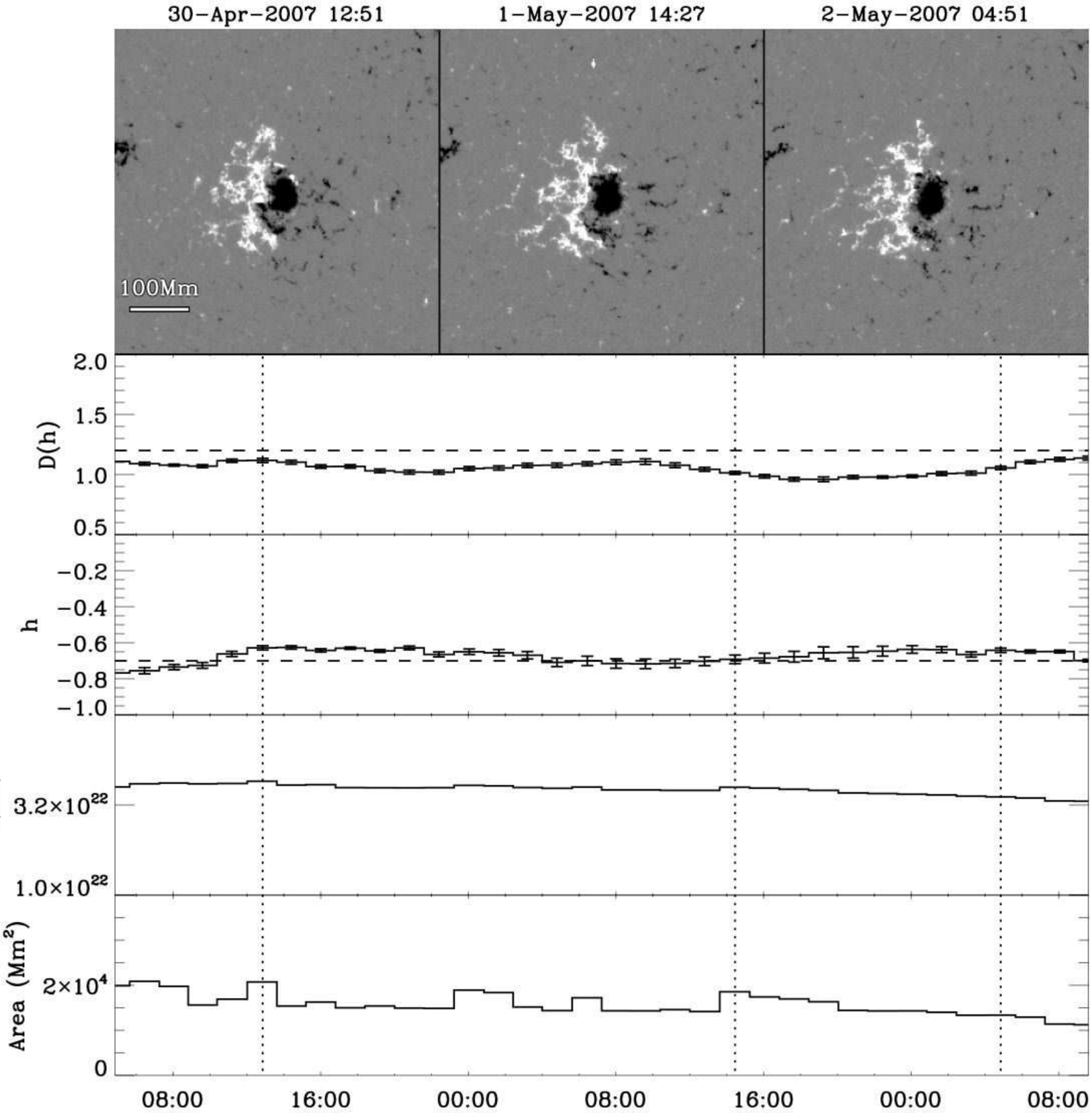

Fig. 3: The evolution of NOAA 10953. (Top panel) MDI magnetogram image for NOAA 10953 on 30 April 2007 at 12:51 UT, 1 May 2007 at 14:27 UT, and 2 May 2007 at 04:51 UT. (Second panel) $D(h)$ for $q = 0$. (Third panel) h for $q = 0$. (Fourth panel) The total unsigned magnetic flux (Mx). (Bottom panel) Total area (Mm^2). Dashed horizontal line in the first panel highlight a previously proposed threshold for flaring (McAteer, Gallagher, and Ireland, 2005). Dashed horizontal line in the second panel shows our proposed threshold.

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